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MEASUREMENTS OF AEROSOLS PRODUCED BY A PROPANE-AIR FLAME IN A CONTROLLED ENVIRONMENT

H. J. Fissan, et al

Minnesota University

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GENERATION AND DECAY OF SMALL IONS

Report Title

MEASUREMENTS OF AEROSOLS PRODUCED BY A PROPANE-AIR FLAME IN A CONTROLLED ENVIRONMENT

to

AIR POLLUTION CONTROL OFFICE

ENVIRONMENTAL PROTECTION AGENCY

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Measurements of Aerosols Produced by a Propane-Air Flame in a Controlled Environment

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to

Air Pollution Control Office
Environmental Protection Agency

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Abstract

Both premixed and diffusion laminar propane-air flames have been burnt in a controlled environment with respect to humidity and particle concentration. The exhaust gases were cooled and diluted and passed through an aerosol charge neutralizer. A Condensation Nuclei Counter and Whitby Aerosol Analyzer were used to determine the concentration and size distributions of the resulting aerosols. The most important parameter controlling the production of particles by this system was found to be the humidity ratio in the system above the flame. For example, under typical conditions as the humidity ratio was varied from 0.007 to 0.014 the measured particle concentration varied from near 0 to approximately 100,000 particle cm^{-3}. Other parameters such as total fuel flowrate and oxidation ratio were found to be of secondary importance. The particles produced by the system were very small, having a median diameter of about 25 Å for a total humidity ratio of approximately 0.014. Although no direct measurement could be made for lower humidity ratios, it appears that particle sizes become even smaller as total humidity ratio is decreased.

Experiments comparing aerosols produced by flames burning in filtered and unfiltered air indicate that a synergistic effect exists, resulting in the production of many more fine particles (Δdiameter <100Å) as well as about a 50% increase in total aerosol volume in the case of the flame burning in unfiltered air.

INTRODUCTION

The formation of particles in flames is of considerable importance from both industrial and environmental points of view. In recent years significant work has been done in the area of solid carbon formation in flames. An excellent survey of this work is given by Gaydon and Wolfhard (1970).

Practically all previous work has been concerned with the soot emitted by flames as carbon black, or with the production and combustion of soot within the flame. The number and size of these particles were determined in most cases by either inserting a cooled probe into the flame or into the exhaust gases and examining the resulting deposits under an electron microscope or by measuring the light scattered by the particles in the flame. Although such techniques are useful in many respects, they tell us very little about the particles, usually very small, which leave the flame and enter the atmosphere from an apparently clean burning system. A recent report of the National Academy of Engineering (1972) focuses attention on fine particles as being one of the principal targets of air pollution abatement in the future. Thus the particles produced by clean combustion are of interest and importance in air pollution as well as the particles produced by obviously dirty combustion. Whitby et. al. (1972) have detected small particles (< 100 Å) in atmospheric aerosols and attribute them to combustion sources. Husar (1971) has actually used a propane flame to act as source of small (~70Å) particles. In Husar's work the flame was merely used as a convenient source of particles, and he therefore did not concern himself with carefully defining the flame conditions.

The work described below is an initial study of particles formed in premixed and diffusion laminar propane air flames. Particle concentrations

and size distributions are measured with a Whitby Aerosol Analyzer and a General Electric Condensation Nuclei Counter. The main experimental parameters investigated are total flow of air through the system in which the flame is burned, the fuel and combustion air flowrates and the humidity in the system. The two main results of this investigation are that particles produced by the propane air flame under the present set of conditions are extremely small and that the observed particle concentrations are very strongly dependent on system humidity.

APPARATUS

The flame is burned in a sealed chamber as shown in Figure 1. The purpose of the chamber is to provide a defined atmosphere surrounding the flame. The chamber is a cube of 0.65 m on the sides and consists of an iron frame covered with aluminum sheets except for the front. The front is covered with a removable plexiglass plate to allow observation of the flame during the experiment. On top of the chamber there is an exhaust stack with an inside diameter of 16 cm. Air is introduced into the chamber with a blower. The humidity of the air is controlled by mixing air dried with silica gel and wet room air in different proportions. The total air flow is monitored with a venturi-flowmeter. Particles are removed from the air with an absolute filter.

Commercial grade propane is used as fuel. It passes through a silica gel dryer and an orifice type flowmeter, and then it passes into a mixing chamber. The combustion air for the premixed flame is taken from the laboratory compressed air line, passed through a silica gel dryer and a calibrated orifice, and then it passes to the mixing chamber. Both fuel and air orifices have been calibrated with a bubble flowmeter. The mixed gases pass through an absolute filter to remove particulates before entering into the burner. The burner is a 1/4 inch copper tube with a slightly flared end for better stabilization of the flame on the burner. The burner is placed in a copper pipe with 3.8 cm inside diameter which leads out of the chamber into a Kr-85 aerosol charge neutralizer (Whitby and Liu 1968) to remove charges from the particles. The neutralizer was used because preliminary experiments indicated that large particle losses occurred, especially in the rubber tubes leading to the measuring instruments, if it is not used. This suggests that most of the observed particles are initially

charged. The copper tube nearest the flame is surrounded with a water jacket in order to cool the inner surface of the tube and the adjacent gases. Hollow, water-cooled copper coils are mounted above this jacket at approximately 30 cm from the bottom of the tube. They provide further cooling of the gases. Inlet pipes were installed to allow the introduction of dilution air into the copper tube between the water jacket and the coils. This air is taken out of the laboratory air supply line, dried and filtered. Its flow is measured with a rotometer. Above the cooling coils, at approximately 60 cm from the bottom of the tube, a thermocouple is located. The water flow to the various cooling elements has been adjusted so that the temperature measured with the thermocouple is never higher than 5° C above room temperature. Thus large temperature changes in the remainder of the system are avoided.

Copper tubing was chosen because an experiment, in which the tube was heated after having been exposed to combusion gases for a long time, showed no particle production unless the tube was heated to red glowing conditions. A similar experiment performed with a pyrex tube showed that particle production began at much lower temperatures.

The flame gases mixed with air from the chamber entrained at the bottom of the copper tube and with the air introduced above the flame are drawn into a 5 gallon plenum chamber and then passed to the particle measuring instruments. A General Electric Condensation Nuclei Counter (CNC) is used for measuring the particle concentration. The nature of this instrument is such that it produced a fluctuating input flow, which in turn causes the flame to visibily pulsate. In order to smooth these fluctuations, a balloon hanging in a slightly depressurized bottle was introduced into the line to the nuclei counter. The average flowrate to the nuclei counter is 6 l min^{-1}. The aerosol size distribution is measured

by introducing a diffusion battery in the line to the nuclei counter. This technique has been described by Husar (1971). In addition, a Whitby Aerosol Analyzer (WAA) is connected to the plenum chamber. The WAA has been discussed in detail by Whitby et. al. (1972 a). It requires a steady flowrate of 9 l min^{-1} of aerosol.

An additional line is connected from the plenum chamber to an exhaust system. The flow through this line is metered and can be varied over a wide range. The total flow through the combusiton system is the sum of the instrument flows, 15 l min^{-1}, plus the flow through this additional line. The system is tested for leakage by running the equipment without the flame and measuring the particle concentration with the CNC. The particle background concentration is about 50 particles cm^{-3}. Introducing unignited flame gases into the system does not lead to any increase of the particle concentration. The flowrate of air from the blower into the chamber is chosen so that no air enters via the exhaust stack. This is checked by monitoring the particle concentration in the exhaust stack. Experiments have also been done to determine if the rate of flow of air into the chamber affects the particle output from the flame. No effect has been observed.

To help to further characterize the system, residence times have been calculated for different flowrates through the system using the known volume of 18.6 liters. The total residence times include a small constant time required to pass through the tubing to the instruments (length 130 cm, inside diameter 1.27 cm). These residence times are plotted in Figure 2. It can be seen that the residence time increases very much below 15 l min^{-1} total flowrate so that processes which depend on the residence time, e.g. coagulation, may become very important below this flowrate.

In order to estimate the losses of particles in the system, the

diffusion and coagulation losses have been calculated for different total flowrates and different particle diameters. For the diffusion losses it has been assumed that the system can be represented by a tube 2.30 m long. The penetration, P, has been determined by using Gormley and Kennedy's equations (Fuchs 1964) for a tube and using Einstein's relation for the calculation of the diffusion coefficients. The penetration through the system has been multiplied by the penetration through the tubing to the instruments to obtain the overall penetration. For the coagulation losses a particle concentration of 10^5 number cm^{-3} has been assumed. This particle concentration was the highest outlet concentration encountered in the present investigation. The total penetration was calculated approximately by adding diffusion and coagulation losses as is shown in Figure 3. Below 15 l min^{-1} the losses are large. They decrease with flowrate and are quite small above 30 l min^{-1}. In order to show the importance of the particle size on the losses, the penetration is shown as a function of the particle diameter in Figure 4 for 29.5 l min^{-1} total flowrate. This is the flowrate at which most of the experiments have been performed. In addition, the penetration curve for diffusion losses alone is plotted. It is seen that the difference between these two curves are minor, indicating that the effect of coagulation for these low particle concentrations is small. The Figure shows a large increase of the losses with decreasing particle size below 50Å. These results can only be regarded as a first estimate of the actual losses, since the system has been idealized as a simple pipe.

PARTICLE PRODUCTION AS A FUNCTION OF TOTAL FLOWRATE

The penetration, P, determined above may be written as

$$P = (N_s - N_e)/N_s$$

where N_s is the particle production rate in the system (particle min^{-1}), and N_e is the rate at which particles are lost by coagulation and diffusion (particles min^{-1}). Then defining N_p, the measured particle production rate (particle min^{-1}), as

$$N_p = N_s - N_e$$

and taking a particle balance gives

$$N_p = nQ_t$$

or

$$N_s P = nQ_t$$

where n is the measured particle concentration (particles cm^{-3}), and Q_t is the total flowrate through the system (1 min^{-1}). If it is assumed that N_s depends only on the flame and is independent of the flowrate through the system, a plot of nQ_t against Q_t should have the same form as the penetration curves determined above. The measured particle production rate N_p (particles min^{-1}) for total flowrates between 15 and 40 1 min^{-1} is given in Figure 5. The experiment is performed for a premixed flame with 0.95 1 min^{-1} propane, 1.18 1 min^{-1} air and a corresponding oxidation ratio, λ, of 0.5. (λ is the ratio of actual to stoichiometric air flow.) All experiments described below are done for this type of flame unless stated otherwise. Figure 5 shows the particle production

rate N_p increasing with increasing flowrate below approximately 30 l min^{-1}; above 30 l min^{-1} N_p seems to be more or less constant. Comparing the shape of the measured curve with that of penetration curves for different particle sizes in Figure 3 shows that the curve for 20 Å diameter particles compares best.

The change of the total flowrate causes parameters other than penetration to change. The flowfield in the vicinity of the flame is changed; however, the effects on the flame in the range of flowrates investigated are believed to be very small. At high flowrates, higher than the ones discussed here, the edges of the flame become rather unstable and stronger fluctuations of the measured particle concentration occur. For this reason flowrates above 38.5 l min^{-1} were excluded. The temperature of the mixed gases detected with the thermocouple located at the end of the cooler decreases slightly with increasing total flowrate.

Because of the water produced by the flame, the humidity of the mixed gases changes with the flowrate. Assuming complete combustion and uniform mixing of combustion products with dilution air, the humidity ratio, W_t, in the system can be calculated and is given in Figure 5. In this calculation it has also been assumed that the gases in the system can be considered to be air. This assumption is justified, because the concentration of CO_2 from combustion is rather small. For a temperature of 25.5 °C, which corresponds to a temperature measured in the plenum chamber, the relative humidity has been calculated. The calculations show that in the range of flowrates covered the humidity ratio changes by a factor of two from W = 0.0095 at 40 l min to W = 0.019 at 15 l min total flowrate. Under the same conditions the relative humidity increases from 60 at 40 l min^{-1} flowrate to 100 percent at 15 l min^{-1}. The relative humidity will change as the gases pass through the system. It is low near the flame because of

high temperatures. The relative humidities presented here are therefore probably high estimates.

INFLUENCE OF HUMIDITY ON MEASURED PARTICLE CONCENTRATION

The effect of the humidity on the measured particle concentration has been investigated. The humidity of the air in the chamber is changed by introducing a dryer in front of the blower and mixing the dried air with different quantities of wet air from the room. The humidity of the air in the chamber is measured with an aspiration psychometer. The flame conditions are the same as described above. The total flowrate is 15 l min^{-1} for all but two runs, each of which is 29.5 l min^{-1}. The measured particle concentration plotted against the humidity ratio in the chamber is shown in Figure 6. All data fell on about the same curve and showed that particle concentration increases strongly with increasing humidity. For a certain flowrate and certain flame conditions a critical humidity exists, above which condensation occurs in the system. Condensation at the cooled surfaces of the copper tube was observed above W = 0.0064, which corresponds to a relative humidity of 100 percent. At this humidity the CNC showed a drastic increase in particle concentration to levels beyond the range of the instrument (> 10^6 particle cm^{-3}). If condensation occurs it takes several hours after decreasing the humidity to bring the system back to stable conditions.

In a second experiment dry secondary air is introduced into the system above the flame. Increasing the flow of dry air decreases the humidity in the system. This also changes the amount of air drawn in at the bottom of the copper tube. In Figure 7 the measured particle concentration is plotted as a function of the secondary air for 29.5 and 38.5 l min^{-1} total flowrate. The conditions of the flame are the same as in the experiments described above. The humidity ratio in the chamber for these two experiments is W = 0.0064. Both curves show a decrease in particle concentration

when the dry secondary air flow is increased. The curve for the flame having the lower total flowrate starts at a higher particle concentration and drops off more rapidly with increasing dry air flow than does the curve for the higher total flowrate. Two additional factors which may influence the particle concentration are changed in this experiment, the humidity and the flowfield in the vicinity of the flame. In order to determine the influence of the humidity, the particle concentration has been multiplied by the total flowrate to give the net particle production rate, and the resulting values N_p (number minute^{-1}) are plotted against the system humidity ratio, W_t, in Figure 8. W_t has been calculated as described above. The results from the experiments discussed in conjunction with Figure 6 (Q_t = 15 and 29.5 l min^{-1}) are also presented in Figure 8. It appears that all of the points for Q_t = 29.5 l min^{-1} fall on the same curve. This is striking because data from two different experiments are presented. In one experiment (illustrated with Figure 6 above) the humidity in the chamber from which air is drawn into the system and passes along the flame is changed. In the other experiment, dry air is introduced above the flame, thus changing the humidity above the flame and the quantity of air drawn in at the bottom of the copper tube. Since the results of both these experiments fall on the same curve of particle production rate versus system humidity, it appears that system humidity is the primary variable involved, and the flowfield and humidity in the vicinity of the flame are only of secondary importance. This suggests that particle production is appreciably influenced by the system above the flame. For all three flowrates a similar and strong dependence of the measured particle production on the humidity ratio occurs. For constant humidity, the production rate of the particles drops markedly with decreasing flowrate. This is probably caused by the increased diffusion and coagulation losses. It may be observed

from Figure 5 that the measured particle production rate as a function of flowrate is relatively constant. However, from Figure 8 it is seen that the particle production rate increased sharply at constant flow as the humidity in the system was experimentally increased. The decrease of relative humidity in the system with increased flowrate (top of Figure 5) is sufficient to cause a sharp decrease in measured concentration with increasing flow if there was not an opposing effect from coagulation and diffusion. The large effect of diffusion and coagulation therefore indicates (Figure 3) that the particle size might be even smaller than the 20 Å estimated earlier.

INFLUENCE OF THE OXIDATION RATIO

In order to test the dependence of particle production on flame conditions, experiments in which the combustion air flowrate, Q_c, is changed while the fuel flow is kept constant at 0.095 l min^{-1}, have been performed. Under the conditions chosen the oxidation ratio has been changed from 0.6 to zero. The total flowrate is kept at Q_t = 29.5 l min^{-1}, and the humidity in the chamber is W_c = 0.0064. The measured particle concentrations are plotted against the combustion air flow and the oxidation ratio in Figure 9. The particle concentration decreases slightly with decreasing oxidation ratio, despite the fact that the flame becomes more and more yellow (indicating that soot particles are present in the flame) with decreasing combustion air. Above Q_c = 1.0 l min^{-1} the flame is blue. In this experiment almost no changes in humidity occur, since Q_c is negligible compared to the total air flow. The changes in the particle concentration reflect, therefore, the effect of oxidation ratio on the particle production. Surprisingly, the particle concentration decreases with increasing amounts of soot in the flame, which suggests that soot doesn't escape from the flame under these conditions. It seems unlikely that soot acts as nuclei for the observed particles, because the particle concentration for a flame in which no soot can be observed is higher than for a pure diffusion flame. This is supported by the fact that preliminary measurements of size distributions for diffusion and premixed flames don't reveal significant differences up to a point at high fuel flowrates where black smoke is produced by the flame. These smoke particles are very large, too large to be classified with the WAA (Dp > 0.6 μ).

THE EFFECT OF TOTAL FUEL FLOWRATE ON PARTICLE CONCENTRATION

The particle concentrations produced by diffusion flames with a total flowrate of 29.5 l min^{-1} and variable fuel flow have been investigated. The resulting plot of particle concentration against fuel flowrate is given in Figure 10. The concentration increases very slowly with flowrate for small flowrates and more rapidly for larger ones. The calculated variation of the system humidity, W_t, is also shown. Most of the concentration changes are due to the changes in humidity (see Figure 8) and not to the changes in flame conditions. However, for fuel flowrates smaller than 0.05 l min^{-1} the curve can't be explained by humidity effects alone.

PARTICLE SIZE DISTRIBUTIONS

It is apparent from the discussion above that the observed particles seem to be very small. In order to get information about the particle size distribution below 40 Å, a diffusion battery containing circular tubes and a manifold for changing the number of tubes is used in series with the CNC. The battery is operated in the same way as described by Husar (1971). For this measurement the following conditions have been used

$$Q_f = 0.095 \text{ l min}^{-1}$$
$$Q_c = 1.18 \text{ l min}^{-1}$$
$$Q_t = 29.5 \text{ l min}^{-1}$$
$$W_c = 0.0064$$
$$\lambda = 0.5$$

These conditions are chosen to give a fairly high particle concentration (~100,000 number cm^{-3}) so that the WAA, which is rather insensitive to low concentrations of small particles, could also be used for the determination of the particle size distribution. The size distribution indicated by the diffusion battery is approximately log-normal with a median diameter of 24 Å and a σg of 2.1. This result is shown in Figure 11 by the full line. In the same figure the size distribution obtained with the WAA is also shown and gives a median diameter of 54 Å and $\sigma g = 1.43$. The σg value is smaller, and the median diameter is larger, because the smallest detectable particle size for this instrument is larger, (~40 Å) and, therefore, the lower part of the distribution is cut off. It is also seen from Figure 11 that both instruments indicate almost no particles having diameters greater than about 200 Å.

It is apparent from the results presented in preceding sections that the humidity in the system is the most important parameter influencing the measured particle production rate. The discussed size distribution refers

to a fixed value of humidity ratio, W_t = o.o138. It is not possible to measure size distributions for humidity levels very much lower than this, because the particle concentration drops off very rapidly with humidity, and these instruments are not sufficiently sensitive for this type of measurement. It is possible, however, to make some estimates of the mean particle diameters at lower humidities by making the following assumptions:

1) The flame produces nuclei at a constant rate.
2) These nuclei grow instantaneously to a diameter which is a function of humidity.
3) These nuclei pass through the system and experience diffusion and coagulation losses which are described by Figure 4 above.

According to this model the measured particle production rates shown in Figure 8 reflect the dependence of penetration upon humidity. The mean particle diameter for the highest production rate (2.64×10^9 number min^{-1}, W_t = 0.0142) shown in Figure 8 for Q_t = 29.5 l min^{-1} has been found above to be 24 Å as measured by the diffusion battery. The penetration for this size particle from Figure 4 is 0.59. The particle diameter at a lower humidity, as for example 0.01, may be found by multiplying the ratio of the production rates at W_t = 0.01 to W_t = .0142 by the penetration corresponding to 24 Å, i.e., 0.59. These penetration values are then used to enter Figure 4 to obtain the particle sizes at different humidity ratios. The results are plotted in Figure 12.

INTERACTION BETWEEN THE FLAME AND AN ATMOSPHERIC AEROSOL

This experiment was performed in order to determine the influence of a flame on an atmospheric aerosol. Particle size distributions have been measured using the WAA with and without a flame burning and with unfiltered air in the chamber. All other parameters were the same as in the experiment described above. The resulting particle number distributions, $\frac{\Delta N}{\Delta \lg Dp}$ and the distribution for the flame in clean air are shown in Figure 3. The particle number concentration for the flame in unfiltered air increases very much for smaller particle sizes. Both experiments in which the flame is burning are done under comparable conditions. Therefore, if no synergistic effects occur, subtracting the filtered air plus flame aerosol size distribution from the lab air plus flame distribution should yield the original lab air distribution. This does not appear to be the case, especially in the small particle size range where many additional particles have been produced through some interaction between the lab aerosol and the flame. This may be partially caused by the different humidities in the system with and without flame, but the increase is so strong that it is likely that the air also provides nuclei which grow into the size range of the WAA as a result of interaction with the flame. The surface and volume distributions for these experiments are shown in Figures 14 and 15 respectively. All the flame plus lab air distributions are of similar shape to those observed for atmospheric aerosols obtained near combustion sources (Whitby et. al. 1972). As diameter increases, both the volume and surface first decrease and then increase in the size range covered by the instrument. Although median diameters for this type of distribution are not very valuable from an absolute point of view, they still characterize the changes occuring in the different experiments.

These diameters are listed in Table 1. The number median diameter of the air and flame distribution is smaller than the one for the air alone, which reflects the tremendous increase of small particles for the flame and air case. The surface and volume median diameters show the opposite behavior. They increase in the case of the flame and lab air, indicating that the number of the larger particles also increase. Similar conclusions can be drawn from the total number, surface and volume concentrations listed in Table 2.

CONCLUSIONS

The experiments described above were intended to characterize the most important parameters involved in the production of particles by a laminar propane flame. The results show that the humidity plays a very important role in the particle formation process. With no flame burning there were no particles observed, and with a flame the particle concentration increased markedly with humidity. It appears that the flame provides nuclei which grow in the presence of water to particles large enough to be transmitted through the system. A change of the oxidation ratio from a blue premixed flame with $\lambda = 0.5$ to a yellow pure diffusion flame results in minor changes in the particle concentration. Since the humidity was constant for this experiment, this change reflects the influence of the flame conditions (oxidation ratio) on the particle concentration, which seems to be minor. A change of the fuel flowrate of the diffusion flame which is accompanied by a change in humidity in the exhaust gases results in particle concentration changes, which may be explained by the humidity changes alone. This again shows the minor importance of the flame conditions and the strong importance of the humidity in the exhaust gases. Particle size distribution measurements with a diffusion battery in series with the CNC and with the WAA demonstrate that the particles are very small. The mean number diameter of the measured size distribution is about 25 Å. The largest particle size observed with either instrument is about 200 Å.

In an additional experiment, in which unfiltered laboratory air was passed alongside of the flame, the particle number concentration increased by about two orders of magnitude in comparison to the laboratory air without the flame. In fact the total particle concentration is much larger than the sum of the particle concentration found in lab air and that pro-

duced by the flame burning in clean air, i.e., there is a synergistic effect. A possible explanation is that the higher humidity in the flame exhaust gases causes nuclei and particles in the air to grow, increasing the number, surface and the volume of the aerosol.

The very small particle size of the combustion aerosols as measured is difficult to explain. Possibly the chemical and physical nature of the aerosols is such that they grow by reaction with water within the system, are partially evaporated with a corresponding small particle size at the time that they pass through the diffusion tube, but are capable of detection because of their hydroscopic nature and in spite of their being smaller than the critical size normally detected by the CNC. It is also possible that these particles retain more charge than would be expected after their passage through the neutralizer.

It is clear that large numbers of small particles are produced by flames, even apparently clean ones. The exact mechanism whereby these particles are produced is still far from clear, however. The experimental system used in this work is, unfortunately, not suitable for a detailed investigation of the production mechanism, because diffusion and coagulation losses and humidity effects are all superimposed. Future work should be initially directed toward reducing these losses and controlling the humidity within the system. Then a systematic investigation of the effect of flame parameters and fuels would probably yield more information on the actual mechanism of particle production.

Table 1 - Median Diameters of Flame Aerosols*
Resulting from Measurements with WAA

Distribution	Diameter (Å)		
	Number	Surface	Volume
Air	87	130	530
Flame	53	66	80
Air plus Flame	45	375	2100

*Flame conditions: Fuel flow = 0.095 l min^{-1}
Combustion air flow = 1.18 l min^{-1}
Oxidation ratio = 0.5
Total air flow = 29.5 l min^{-1}
Chamber humidity ratio = 0.0064

Table 2 - Total Concentrations of Flame Aerosols*
Resulting from Measurements with WAA

Distribution	Number (number cm^{-3})	Surface (μ^2 cm^{-3})	Volume (μ^3 cm^{-3})
Air	2.08×10^4	72	1.9
Flame	1.26×10^5	18.2	.024
Air plus flame	4.73×10^5	154	2.75

*Flame conditions: Fuel flow = 0.095 l min^{-1}
Combustion air flow = 1.18 l min^{-1}
Oxidation ratio = 0.5
Total air flow = 29.5 l min^{-1}
Chamber humidity ratio = 0.0064

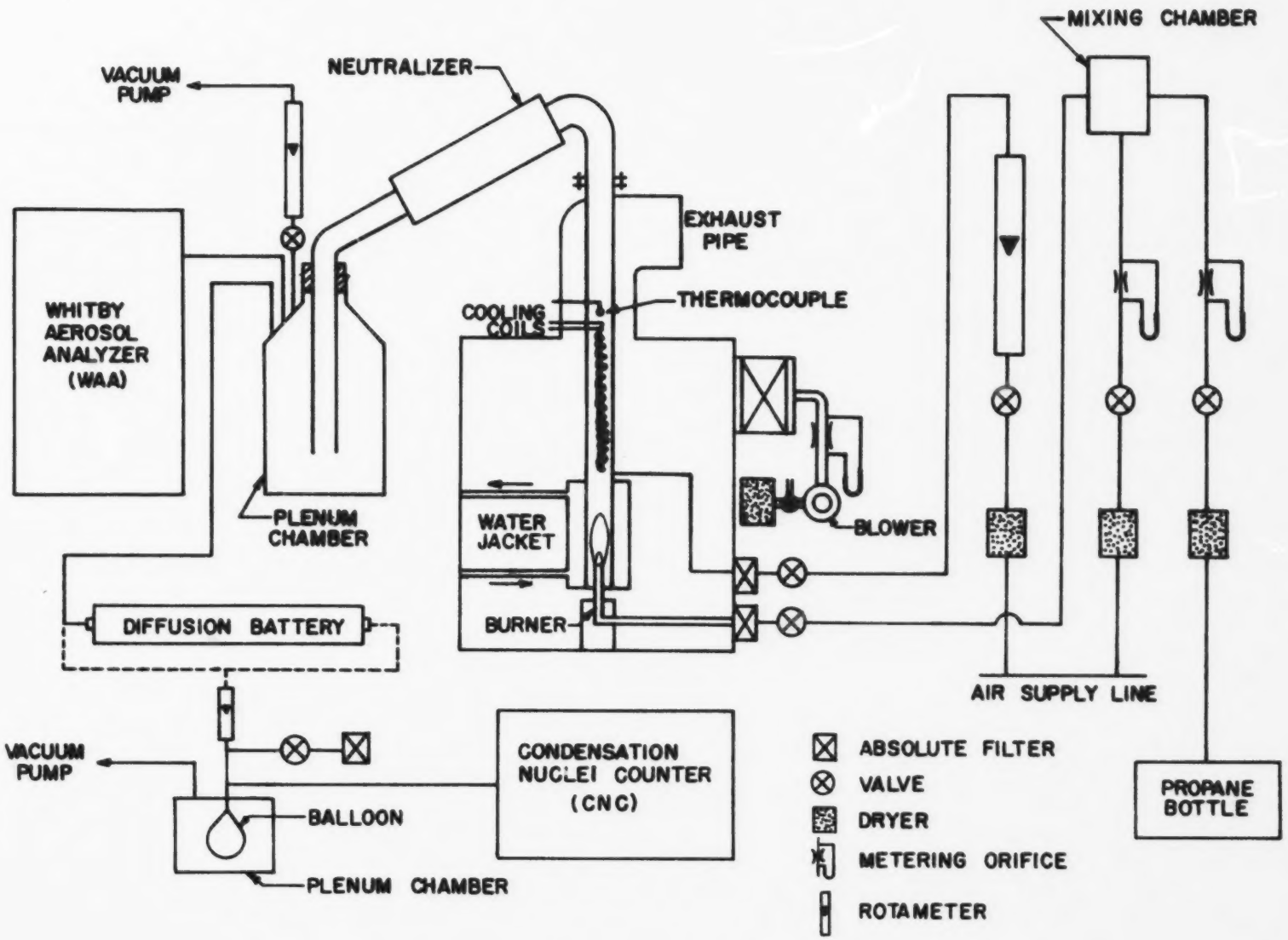

Figure 1. Apparatus

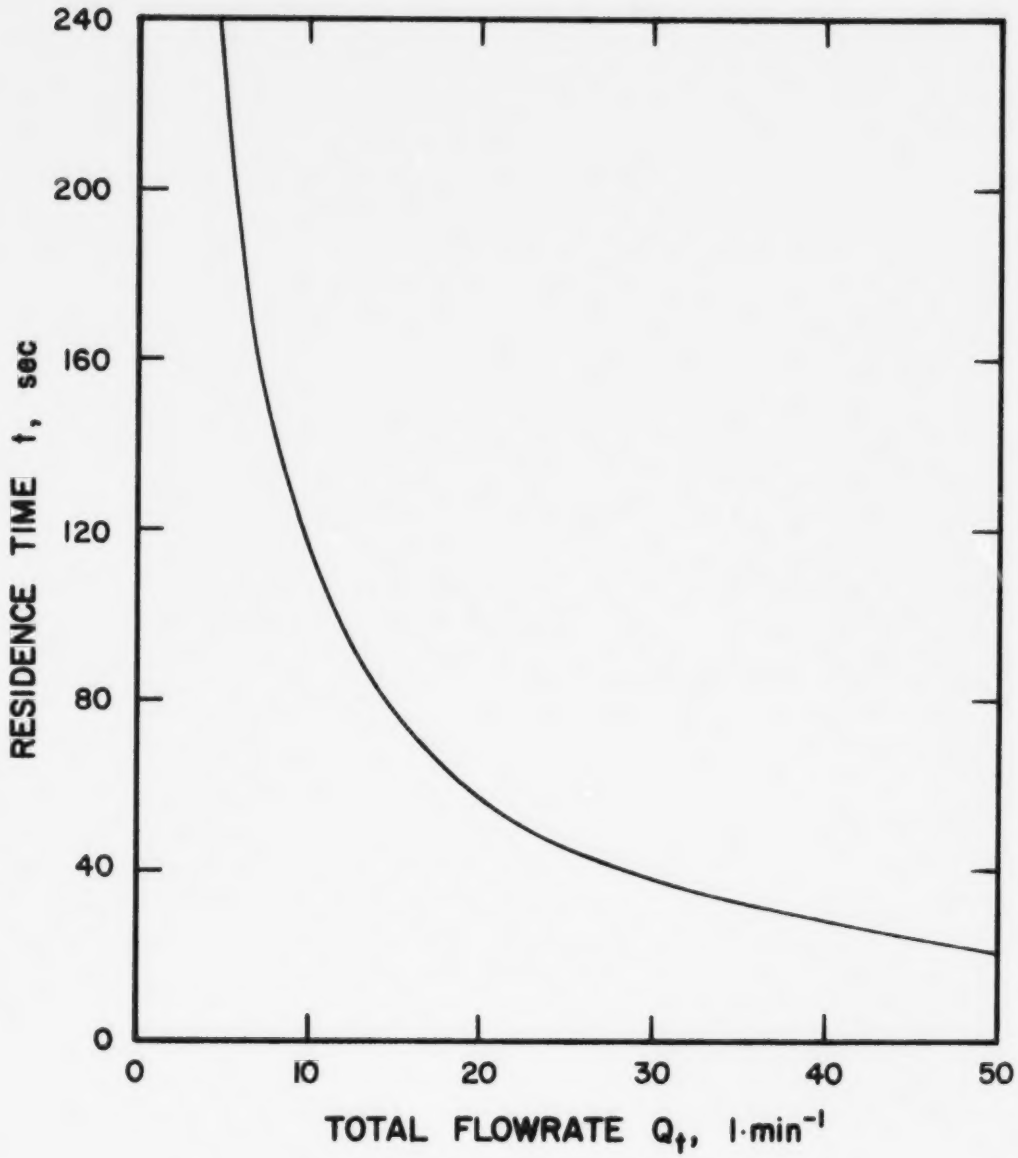

Figure 2. Total Residence Time of Gases in the System Plotted against Total Flow Rate through the System.

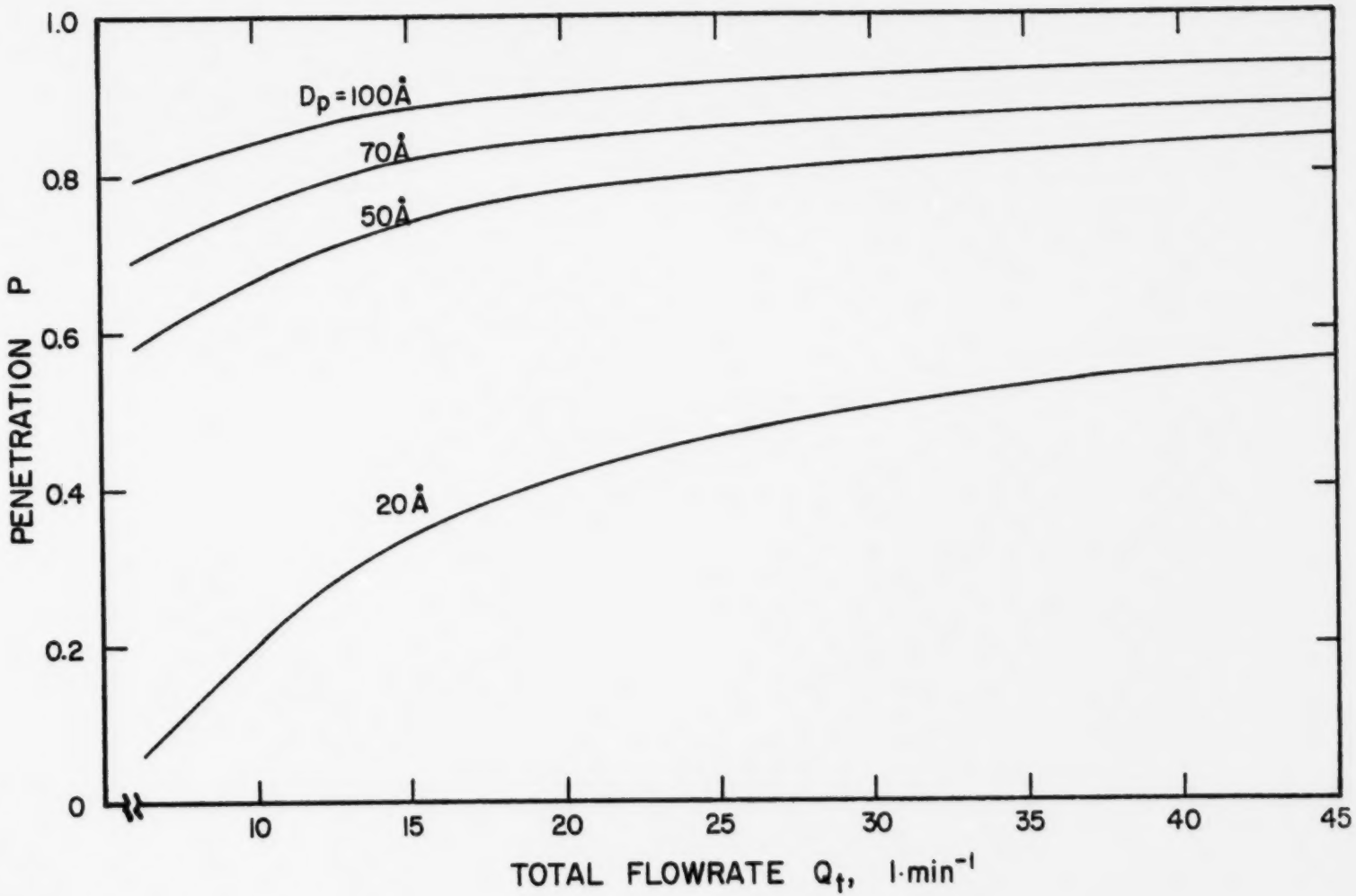

Figure 3. Calculated Penetration of Monodisperse Aerosols through the System Plotted against Total Flow Rate through the System.

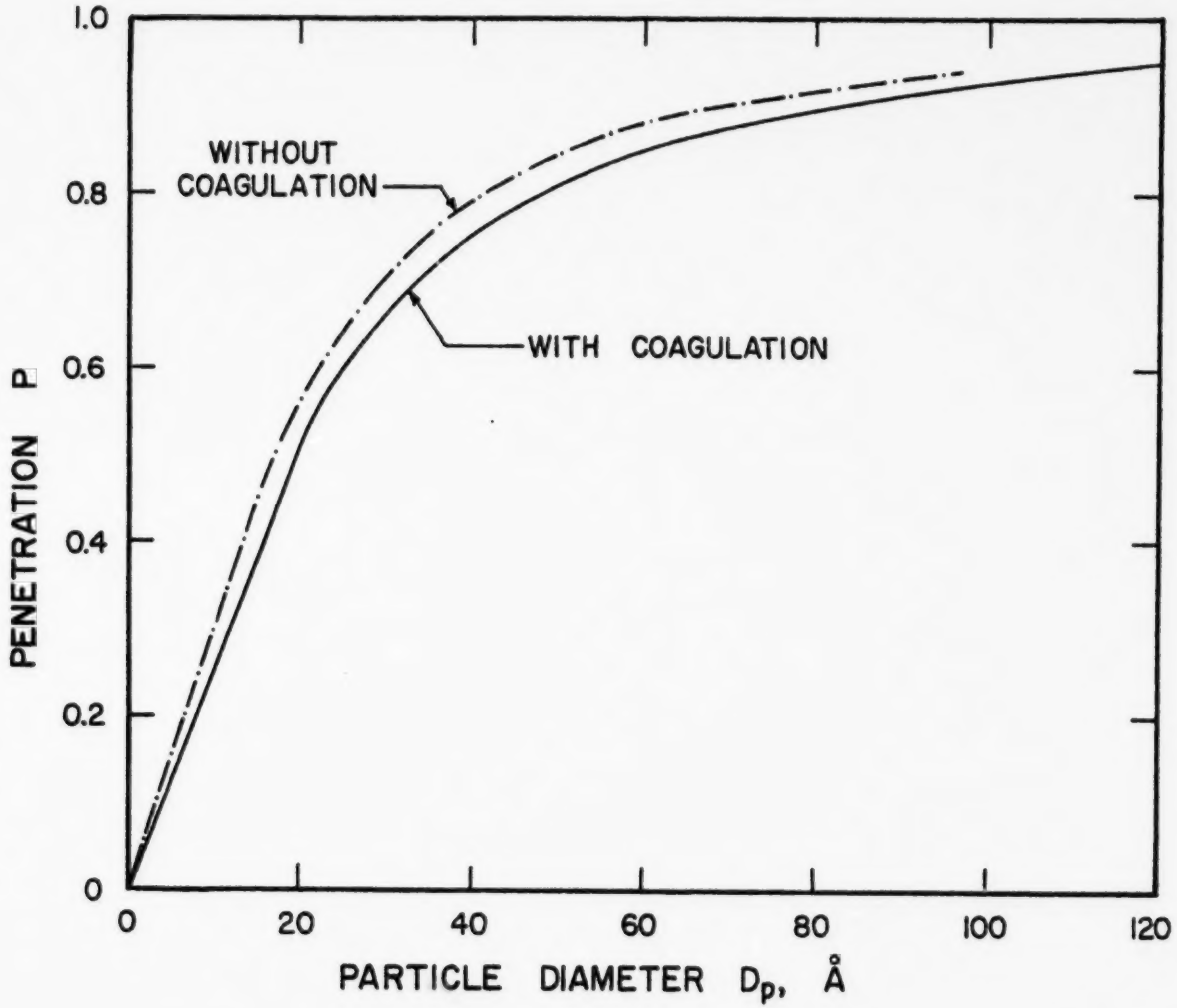

Figure 4. Calculated Penetration through the System Plotted against Particle Diameter. The Total Flow Rate is Fixed at 29.5 $1.min^{-1}$.

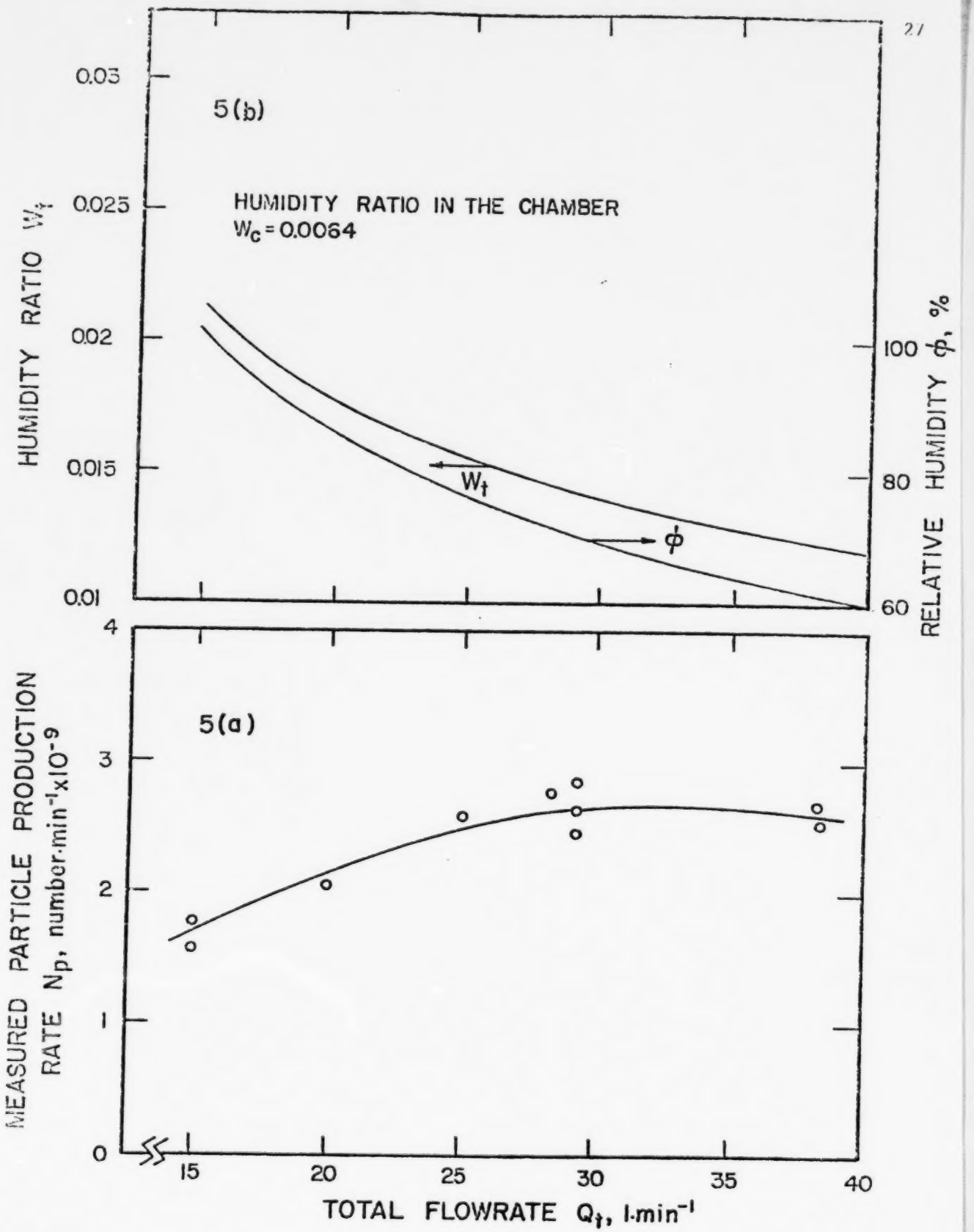

Figure 5(a). Particle Production Rate and 5(b). Humidity in the System Plotted against Total Flow Rate through the System. Premixed Flame, Fuel Flow Rate = 0.095 l.min^{-1}, Combustion Air Flow Rate = 1.18 l.min^{-1}, $\lambda = 0.5$.

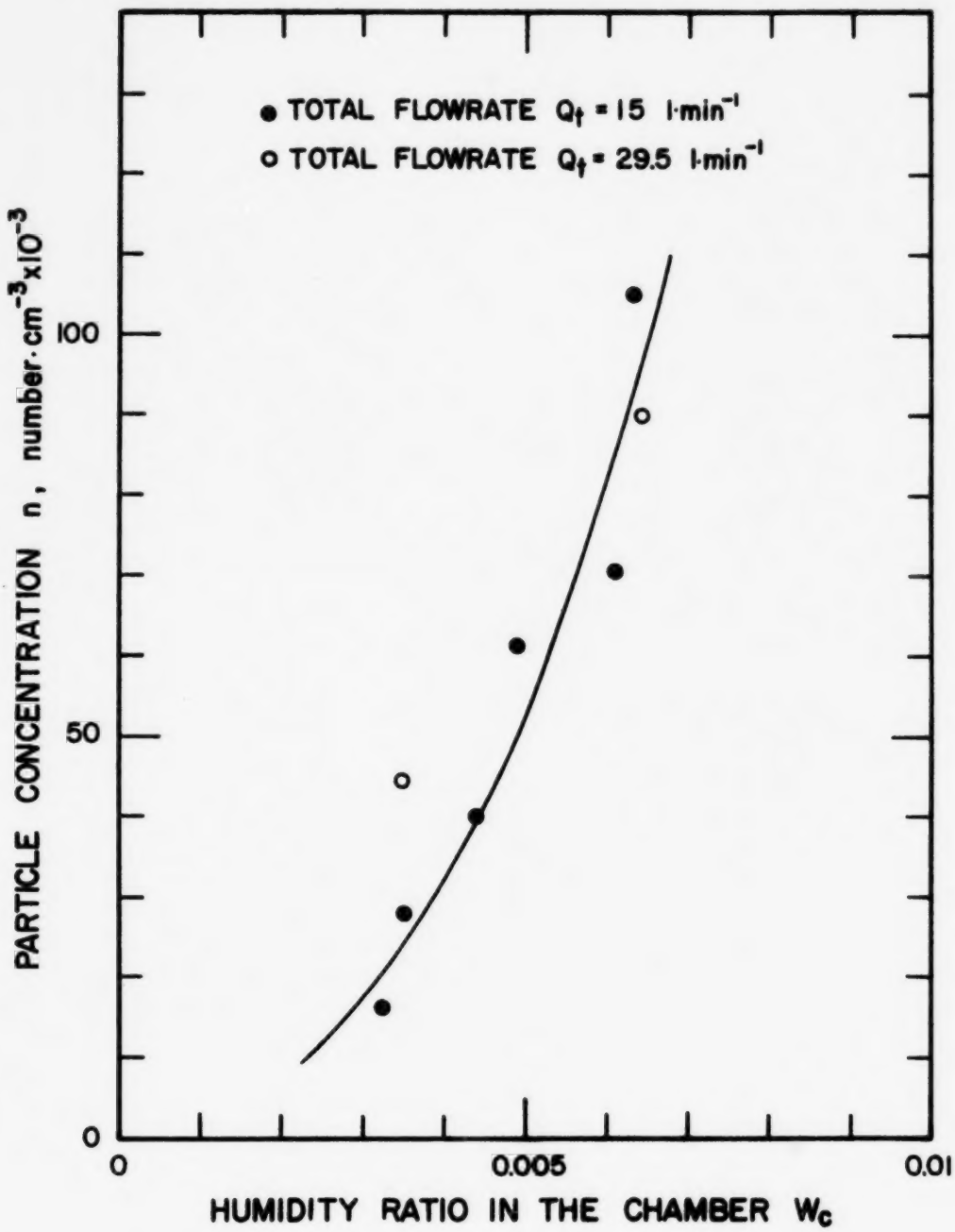

Figure 6. Measured Particle Concentration Plotted against Humidity in the Chamber. Premixed Flame with 0.095 l.min^{-1} Fuel Flow and 1.18 l.min^{-1} Combustion Air Flow. λ = 0.5

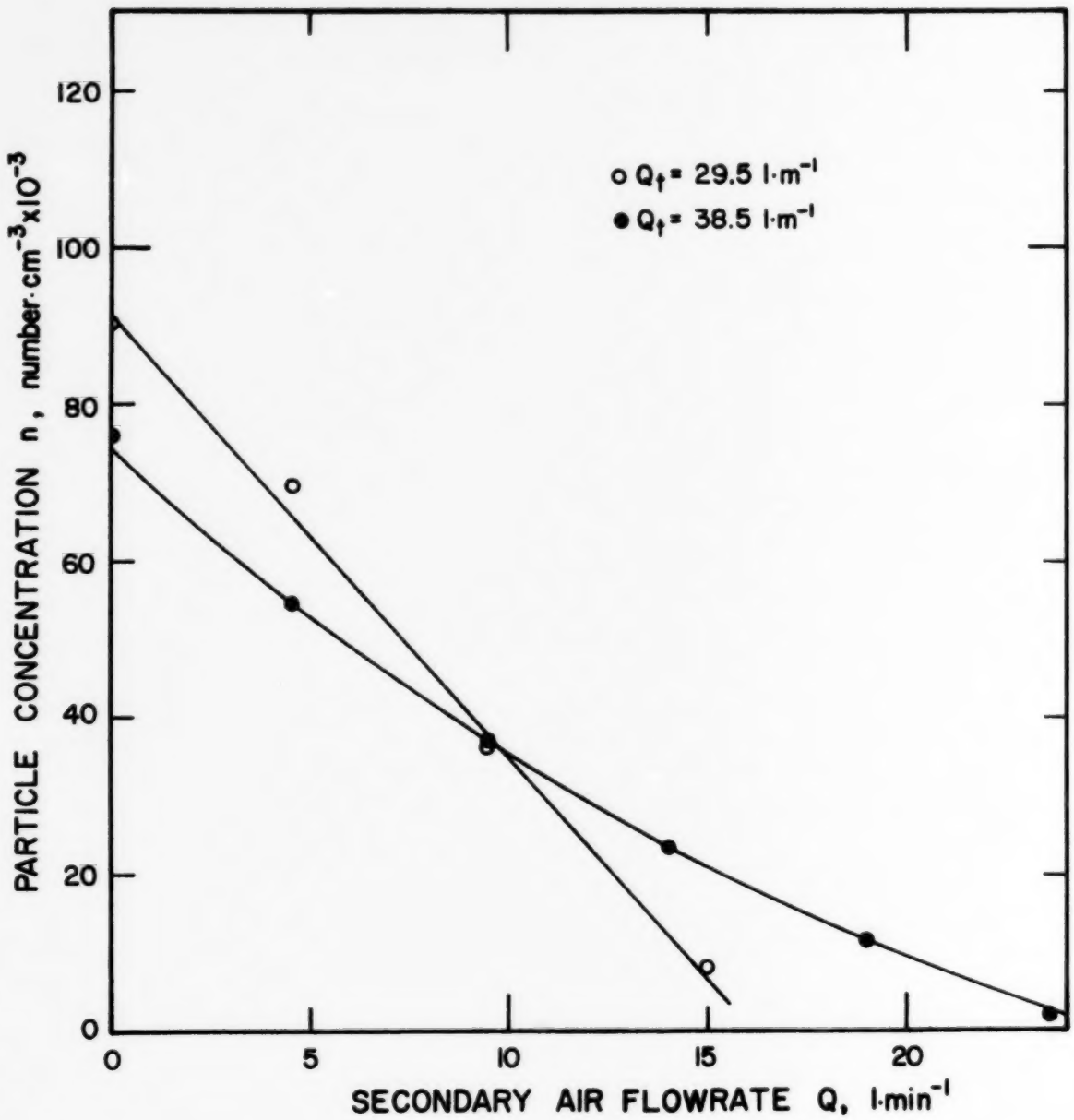

Figure 7. Measured Particle Concentration Plotted against the Rate of Air (Secondary) Addition above Flame. Premixed Flame with 0.095 and 1.18 l.min^{-1} Fuel and Combustion Air Flows, Respectively. λ = 0.5

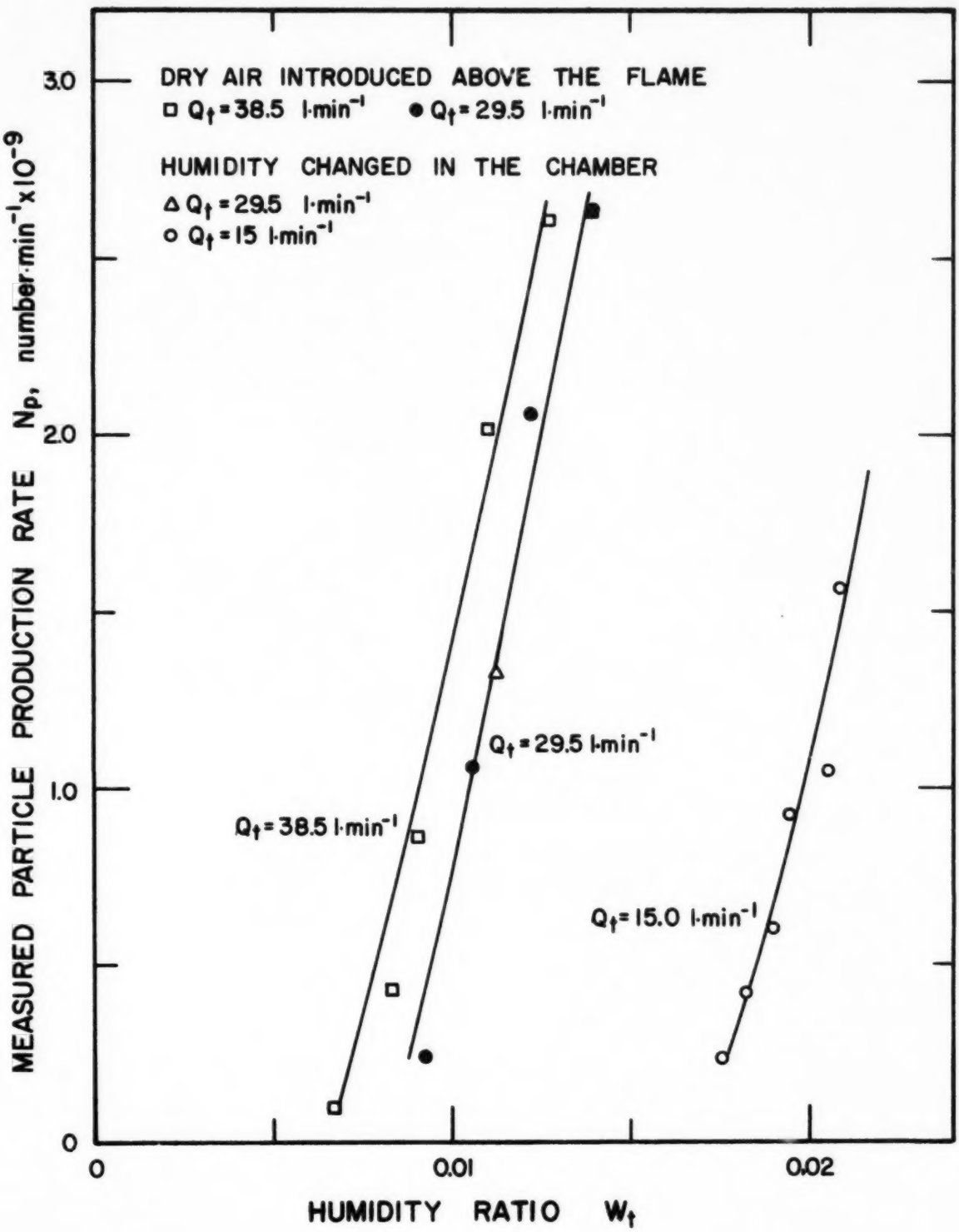

Figure 8. Measured Particle Production Rate Plotted against Humidity in the System. Premixed Flame with Fuel Flow 0.095 l.min^{-1} and Combustion Air Flow 1.18 l.min-1. λ = 0.5

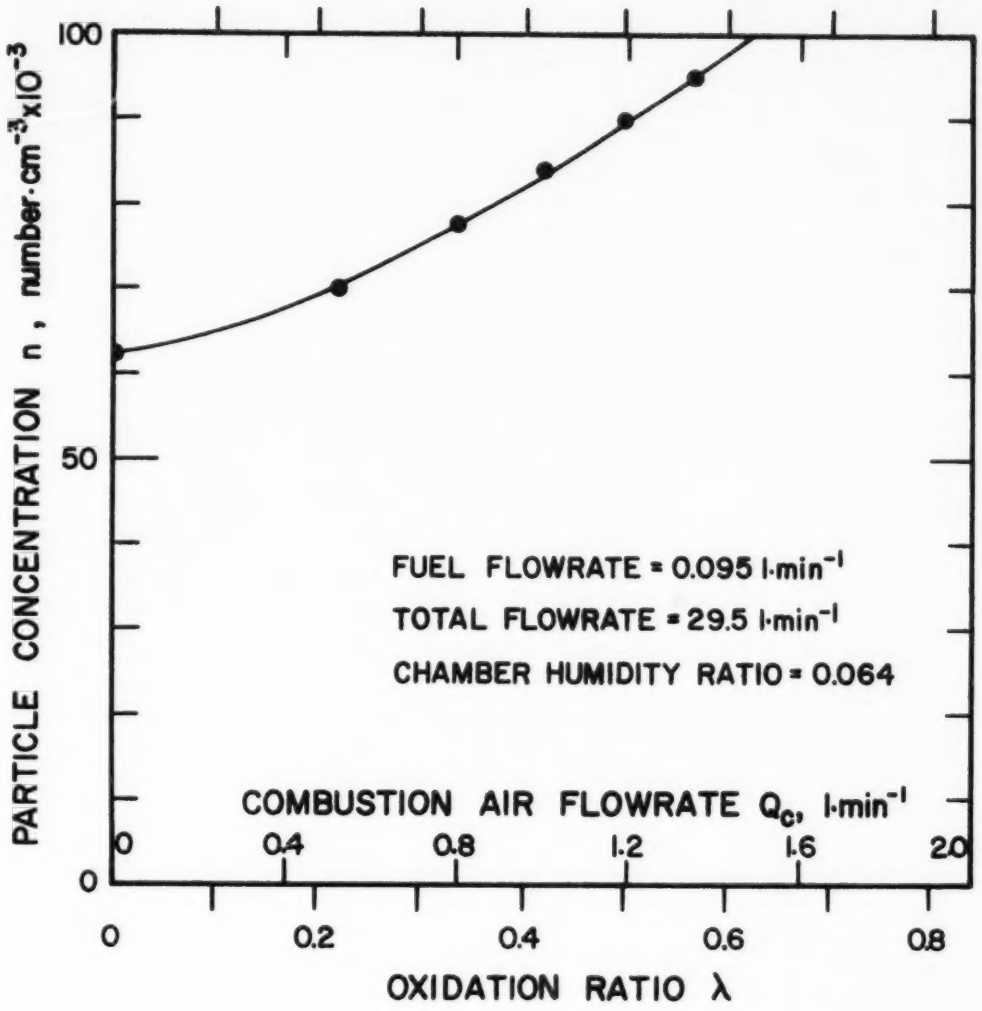

Figure 9. Measured Particle Concentration Plotted against Combustion Air Flow and Oxidation Ratio.

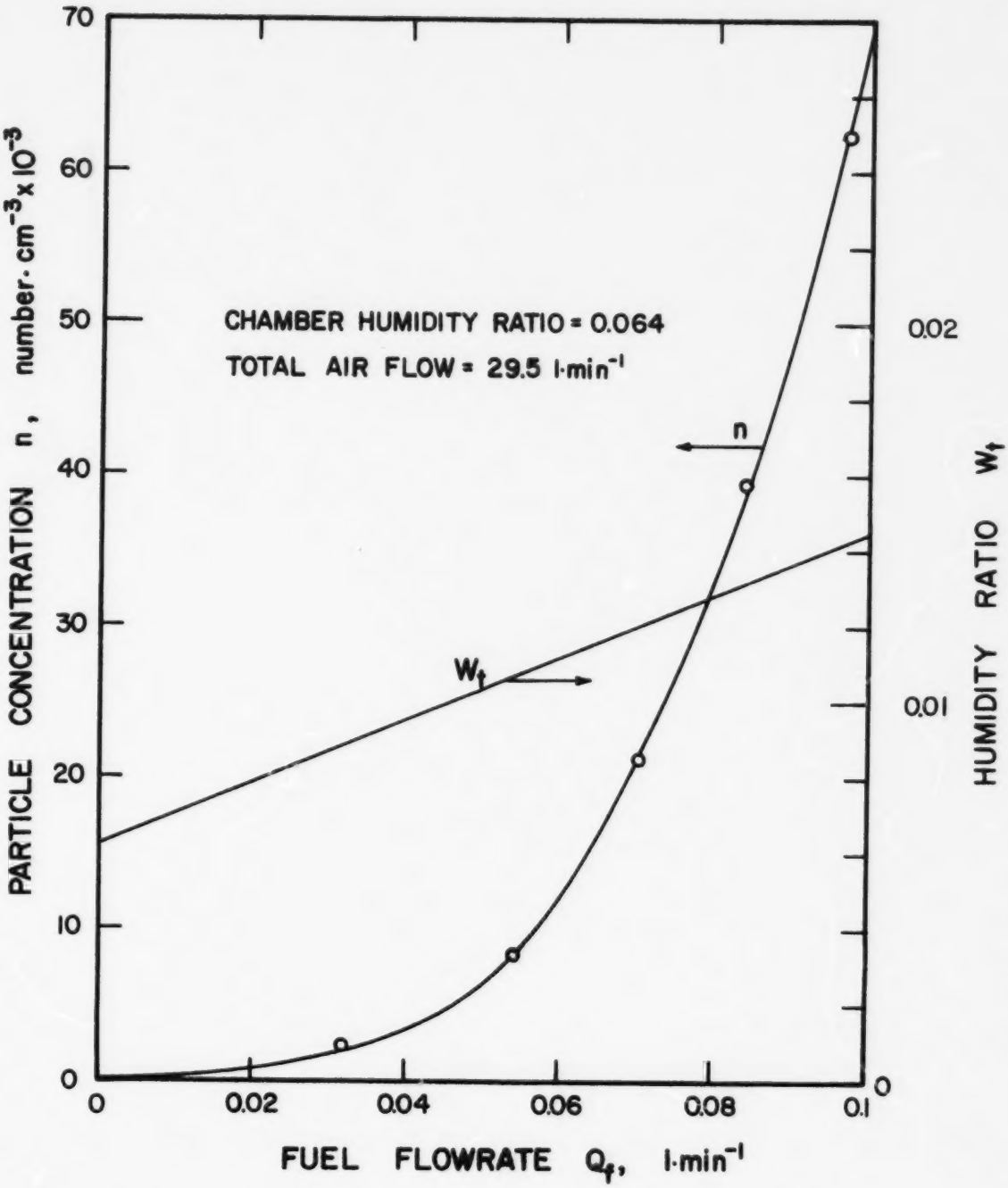

Figure 10. Particle Concentration and System Humidity Ratio produced by a Diffusion Flame Plotted against Fuel Flow Rate.

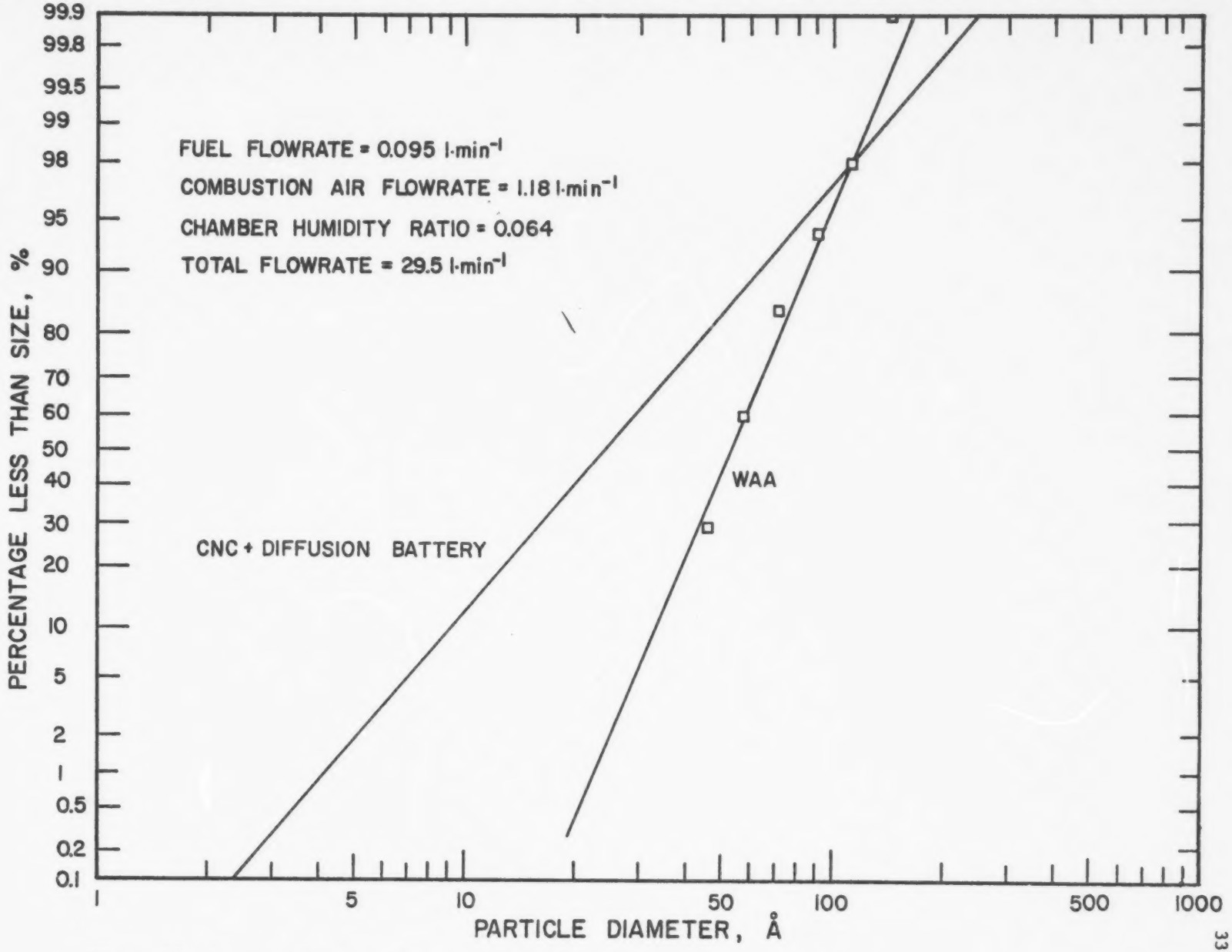

Figure 11. Measured Particle Size Distributions Produced by a Premixed Flame.

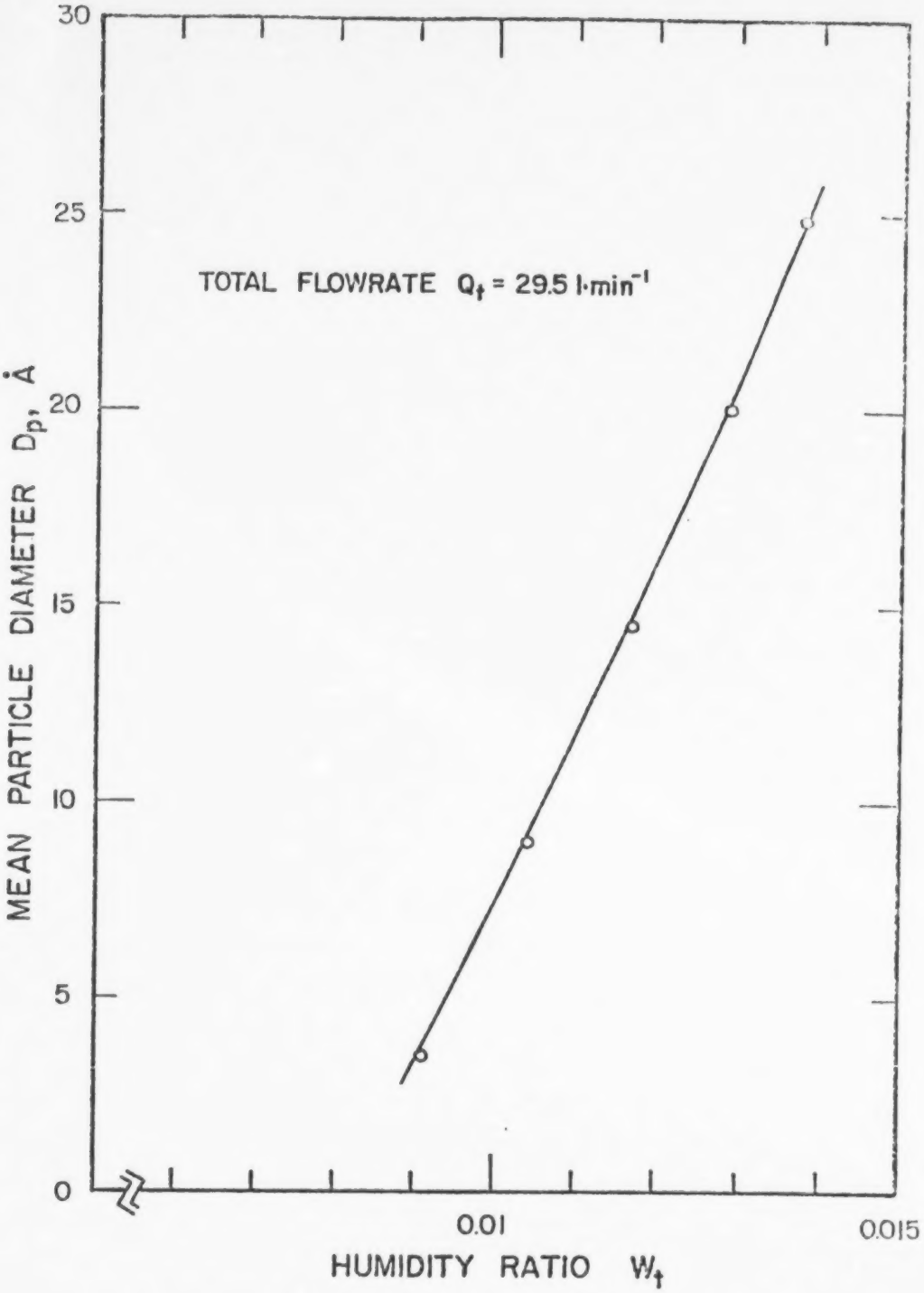

Figure 12. Calculated Mean Particle Diameter Produced by a Premixed Flame, Fuel Flow Rate = 0.095 l.min^{-1}, Air Flow Rate = 1.18 l.min^{-1}, λ = 0.5.

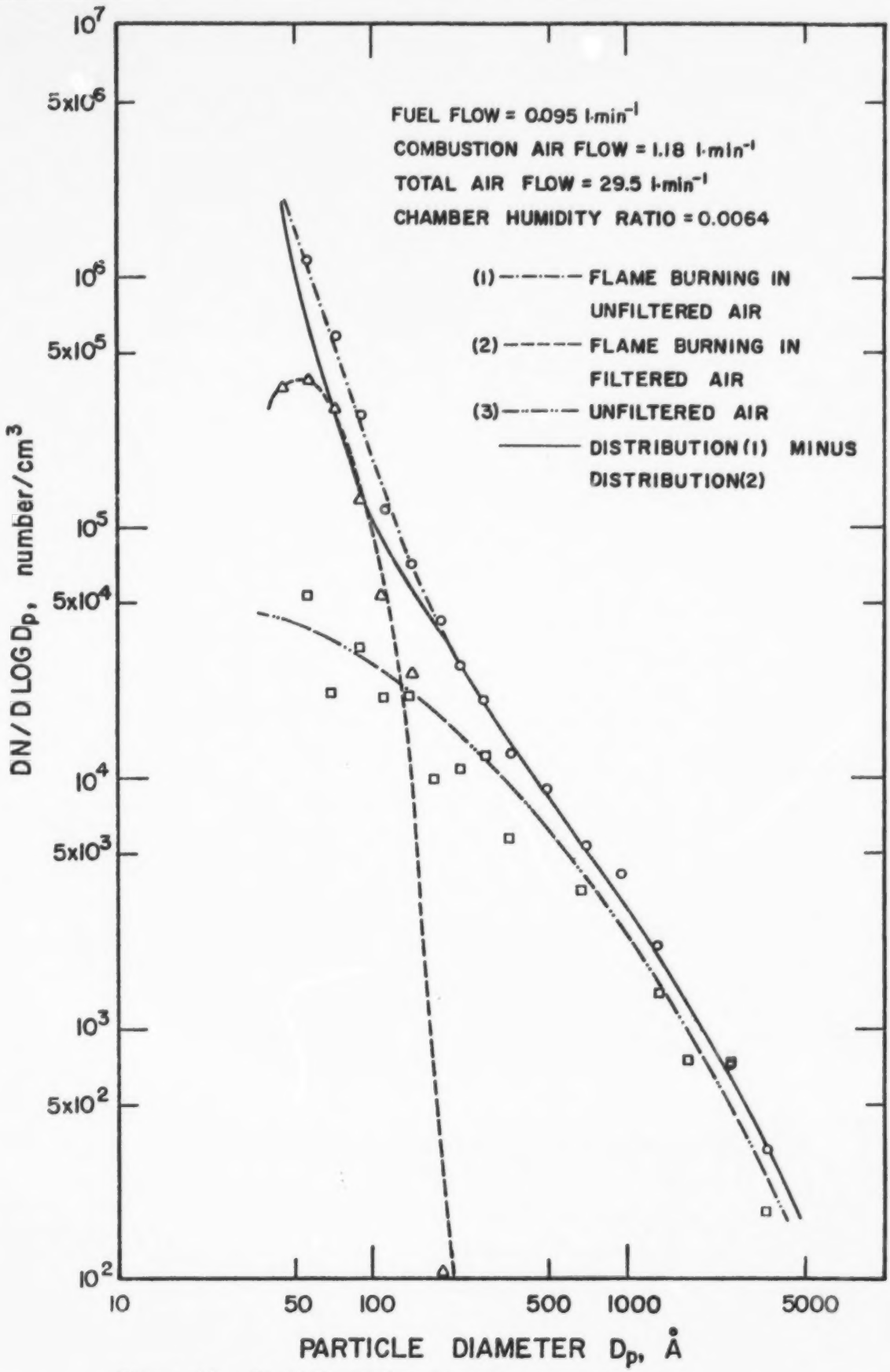

Figure 13. Particle Number Distributions Obtained with the Whitby Aerosol Analyzer.

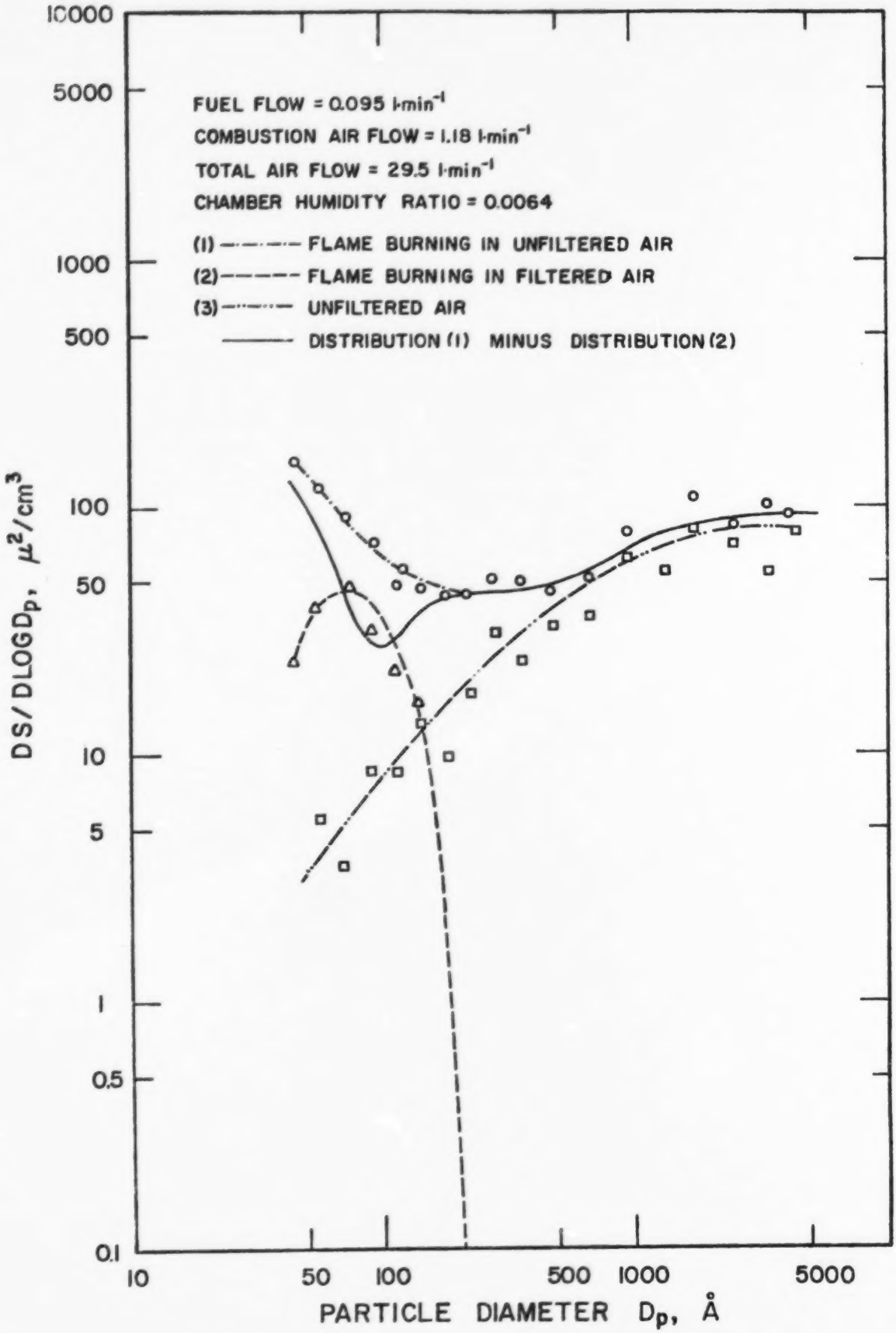

Figure 14. Measured Surface Area Distribution Obtained for Flame Aerosols.

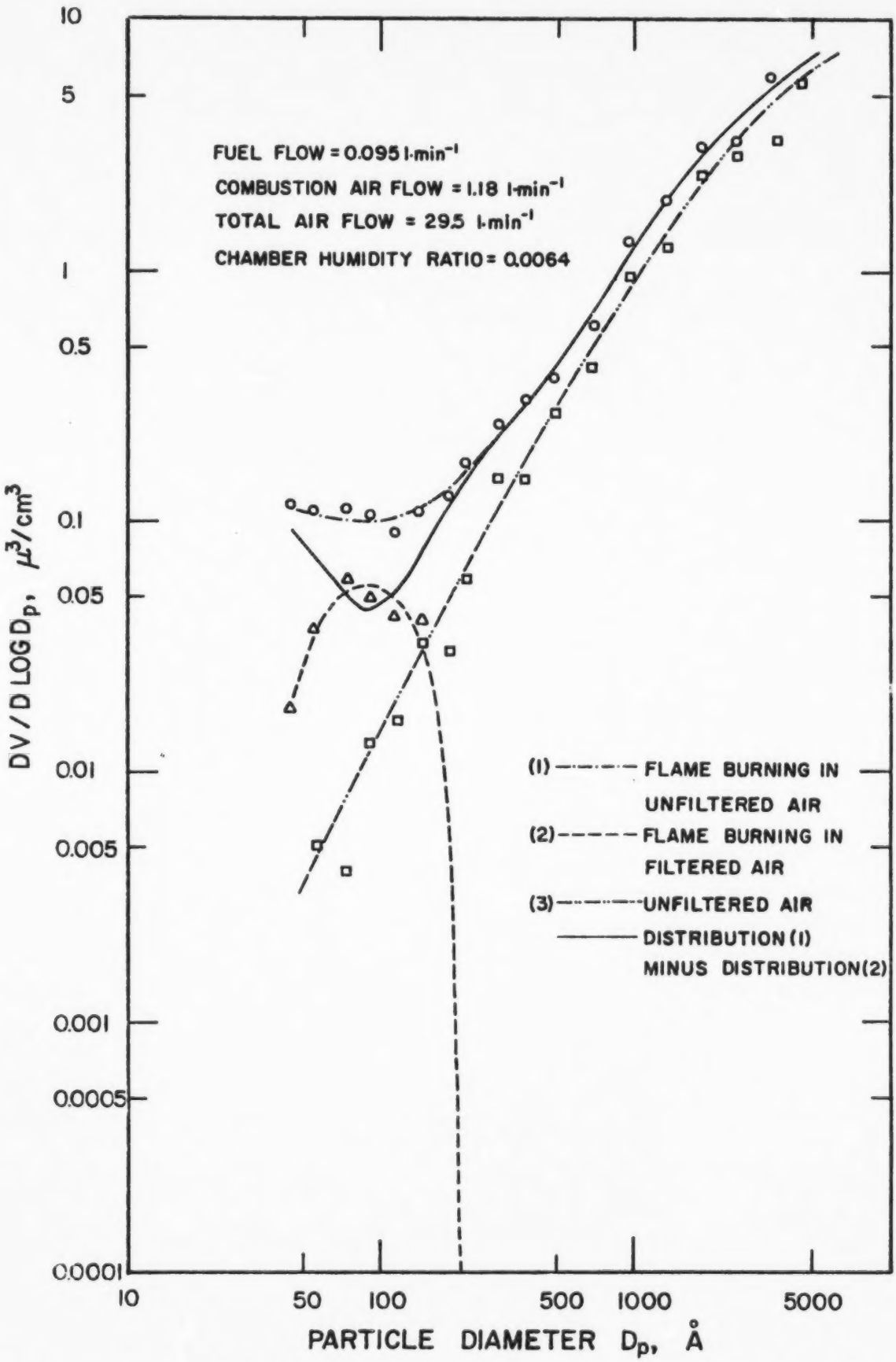

Figure 15. Measured Volume Distribution Obtained for Flame Aerosols

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